

United States Patent Application for:

**GENERATING ELECTRONS WITH AN ACTIVATED PHOTOCATHODE**

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## CROSS REFERENCE

5 This application is a continuation-in-part of U.S. Patent Application no. 10/282,324, filed on October 10<sup>th</sup>, 2002, entitled "ELECTRON BEAM PATTERN GENERATOR WITH PHOTOCATHODE COMPRISING LOW WORK FUNCTION CESIUM HALIDE", by Maldonado et al., which is incorporated herein by reference in its entirety.

## GOVERNMENT SUPPORT

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At least a portion of the work related to the invention described herein was performed with Government support under Contract Number N581-99C-8624. The Government has certain rights in these portions of the invention.

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## BACKGROUND

Embodiments of the present invention relate to the generation of electron beams and their applications.

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Electron beams are used in a number of different applications. For example, electron beams can be modulated and directed onto an electron sensitive resist on a workpiece, such as a semiconductor wafer or mask, to generate an electron beam pattern on the workpiece. Electron beams can also be used to inspect a workpiece by, for example, detecting electrons emerging or reflected from the workpiece, to detect defects, anomalies or undesirable objects. Electron beams can also be used to irradiate a workpiece, such as a postal envelope, to destroy toxic chemicals or harmful microorganisms therein.

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A typical electron beam apparatus comprises an electron beam column that includes an electron beam source to generate one or more electron beams and electron beam elements to focus or deflect the electron beams across a workpiece, which is held on a movable support. The electron beam source typically comprises a photocathode and wavelength matched radiation beam source. The photocathode can be a radiation transparent workpiece coated with an electron-emitting material. The electron-emitting material has an electron work function, which is the minimum electron

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emission energy level required to emit an electron from the surface of the material. A beam source directs radiation onto the backside of the transparent workpiece, the radiation having an energy level that is at least as high as the electron work function. When photons of the beam impinge on the electron-emitting material they excite

5 electrons to a suitable energy level that emits the electrons from the electron-emitting material. For example, one photocathode-laser combination comprises an argon-ion laser, a frequency multiplier crystal, and a photocathode comprising a electron-emitting material of Mg or MgO. The argon-ion laser has a fundamental wavelength of 514 nm, which is reduced to 257nm by the frequency multiplier crystal, to generate a laser

10 beam having an energy level of about 4.8 eV. The frequency multiplied 4.8 eV laser beam has a higher energy than the workfunction of the Mg or MgO electron-emitting material, which is 3 to 4 eV, thus, the laser system and the electron-emitting material are suitably matched.

15                    Electron-emitting materials used in such conventional photocathode systems have several limitations. For example, electron-emitting magnesium gradually oxidizes from exposure to residual oxygen in a low-pressure environment. MgO emitters often gives rise to deleterious blanking effects when the incident laser beam is blanked, i.e., turned on after an off period, when modulating the electron beams. In

20 another example, the emission spot of a CsTe electron-emitting material often grows in size in operation, requiring the electron-emitting material to be patterned or covered with a protective anti-oxidation layer of CsBr, as described in commonly assigned U.S. patent application publication no. US 2003/0042434A1, which is incorporated herein by reference in its entirety. Cesium antimonide electron-emitting materials also have to

25 be covered with a protective layer of CsBr to minimize attenuation of the quantum efficiency of the electron-emitting over time in an oxygen environment, as described in U.S. patent no. US 6,531,816 B1, which is also incorporated herein by reference in its entirety.

30                    A further problem with conventional electron beam apparatus arises from their throughput versus resolution trade-off. Conventional apparatus that use a single electron beam to scan across a workpiece provide relatively low throughput when used at high resolutions. For example, at current line width resolutions of 100 to 130 nm, a single electron beam system takes about 6 hours to scan across the entire surface of a

35 200 mm workpiece; however, at resolutions of 35 to 50 nm, the same system would

take about 50 hours to scan the same workpiece. This problem is reduced in multiple electron beam apparatus, which use a plurality of electron beams drawn from one or more electron sources as separate and well-defined beams. The multi-beam systems provide higher throughput and speed even at high resolutions. However, even these

5 multi-beam systems are limited by the degradation, low beam current and electron cross-over limitations of conventional photocathodes.

Thus, it is desirable to have an electron generating system that can generate a consistent stream of electrons without deleterious changes in operation. It

10 is further desirable to have a properly matched photocathode and beam source capable of generating electrons with good efficiency and consistent emissivity. It is also desirable to have a stable photocathode that does not degrade due to oxidation in the vacuum environment. It is further desirable to have an electron beam apparatus capable of providing good throughput at high resolutions.

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## SUMMARY

An electron beam apparatus comprises a radiation beam source to generate a radiation beam and a photocathode comprising an electron-emitting material composed of activated alkali halide having a minimum electron emission energy level that is less than 75% of the minimum electron emission energy level of the un-activated alkali halide. The electron-emitting material emits electrons when the radiation beam is incident thereon. Electron beam elements are provided to form an electron beam from the emitted electrons and direct the electron beam onto a workpiece. A support is provided to support the workpiece.

In one version, the photocathode comprises an electron-emitting material composed of activated alkali halide having a minimum electron emission energy level that is less than about 5 eV, such that the electron-emitting material emits electrons when a laser beam having a wavelength of from about 190 to about 532nm is incident thereon.

In another version, an electron beam pattern generator generates a pattern of electrons on a workpiece. The pattern generator comprises the aforementioned photocathode, and a laser beam source to generate the laser beam having a wavelength from about 190 to about 532 nm. A beam modulator is provided to modulate the intensity of the laser beam according to a pattern and direct the modulated laser beam onto the photocathode. Electron beam elements are used to form an electron beam from the emitted electrons and direct the electron beam onto a workpiece. A support is provided to support the workpiece.

Yet another version comprises an electron beam inspection apparatus that is used to inspect a workpiece with electron beams. The apparatus comprises the aforementioned photocathode and a laser beam source to generate a laser beam having a wavelength from about 190 to about 532.nm. Electron beam elements are used to form an electron beam from the emitted electrons and direct the electron beam onto a workpiece. A support supports the workpiece. An electron detector is used to detect electrons backscattered from the workpiece to inspect the workpiece.

In an electron generating method, an electron-emitting material composed of alkali halide is provided. The alkali halide is activated to form an

activated alkali halide having a minimum electron emission energy level that is less than 75% of the minimum electron emission energy level of the un-activated alkali halide. A first radiation beam is directed on the activated alkali halide, the first radiation beam having photons with an energy level that is higher than the energy level of the activated alkali halide to cause electrons to be emitted therefrom.

A method of manufacturing a photocathode for an electron beam apparatus comprises providing a substratum in a process zone, evacuating the process zone, evaporating an alkali halide in the process zone to deposit alkali halide on the workpiece, and activating the deposited alkali halide to have a minimum electron emission energy level that is less than 50% of the electron emission minimum electron emission energy level of the un-activated alkali halide by directing radiation onto the deposited alkali halide for a sufficient time period to develop an interior region having a first alkali concentration and a surface region having a second alkali concentration. The second alkali concentration results from a capping layer of alkali formed on the surface of the material.

## DRAWINGS

These features, aspects, and advantages of the present invention will become better understood with regard to the following description, appended claims, and accompanying drawings which illustrate exemplary features of the invention. However, it is to be understood that each of the features can be used in the invention in general, not merely in the context of the particular drawings, and the invention includes any combination of these features, where:

Figure 1 is a sectional side view of a photocathode comprising an electron-emitting material comprising alkali halide with a concentration gradient of alkali;

Figure 2 is a schematic diagram of a photocathode deposition system capable of making the photocathode of Figure 1;

Figure 3 is a schematic diagram of an embodiment of an electron beam apparatus having a beam source section, an electron beam section, and a controller;

Figure 4 is a schematic diagram of an embodiment of a laser beam section of an electron beam apparatus;

Figure 5 is a sectional side view of an electron beam section of an electron beam apparatus;

Figure 6 is a schematic diagram of an embodiment of a computer-readable program executable by the controller shown in the apparatus of Figure 3;

Figure 7 is a block diagram of an embodiment of a data path for generating a raster scanning data pattern;

Figure 8 is a plot of electron emission output over time for a CsBr photocathode illuminated by an argon-ion laser;

Figure 9 is a schematic diagram of an embodiment of an electron beam inspection apparatus; and

Figure 10 is a schematic diagram of an embodiment of a computer-  
5 readable program to operate the electron beam apparatus.



## DESCRIPTION

Electrons are generated from a photocathode **20** comprising a substratum **22** supporting an electron-emitting material **24**, as illustrated in Figure 1.

5 The photocathode **20** is typically a negatively biased electrode, but may also be at a floating or ground potential. The electron-emitting material **24** absorbs photons that excite electrons above the energy level of a surrounding vacuum environment, and a portion of the electrons that are sufficiently excited are emitted into the vacuum. Thus, the electron-emitting material **24** is a material has a minimum electron emission energy level that is sufficiently low to emit electrons when photons having an energy greater than the minimum electron emission energy level are incident upon and absorbed by the electron-emitting material **24**. The substratum **22** typically comprises a radiation permeable material that is permeable to radiation in a predefined band of wavelengths, so that the radiation can pass through the substratum **22** to reach the electron-emitting material **24**. For example, the substratum **22** may comprise sapphire. The photocathode **20** can also have a conductive layer **26** between the substratum **22** and the electron-emitting material **24** to provide a good adhesion layer that also serves as an electrode to complete the photocurrent circuit and is substantially transparent to the radiation. If the radiation is impinging from the photocathode side, the conductive layer may be opaque to the incident radiation wavelength. The conductive layer may also include materials with good adhesion and low chemical reactivity with the photocathode like Mo, Cr and Ta. While an illustrative embodiment of the photocathode is described, it should be understood that other embodiments are also possible, such as embodiments in which there is no substratum and the photocathode is made entirely from the electron emitting material, or others which have different shapes or which use different layers, thus, the scope of the claims should not be limited to the illustrative embodiments.

The photocathode **20** comprises an electron-emitting material **24** composed of an activated alkali halide that emits electrons when excited with radiation having a minimum electron emission energy level higher than the minimum electron emission energy level of the un-activated material. The alkali metals, found in Group I of the periodic table (formerly known as group IA), are reactive metals that have only one electron in their outer shell, and can lose that one electron in ionic bonding with other elements. The alkali metals include lithium, sodium, potassium, rubidium, cesium

and francium. The halogens of Group VII of the periodic table include chlorine, fluorine, bromine and iodine. The alkali halide material comprises at least one alkali metal and at least one halogen in a ratio that may be a stoichiometric or non-stoichiometric ratio.

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Of the alkali halides, cesium halide materials have been found to have good results, although the other alkali halides may also be used. The cesium halide material comprises at least one cesium atom and at least one halogen atom. The cesium halide is not necessarily limited to particular stoichiometric formulations of conventional cesium halides, but can include non-stoichiometric formulations that provide a desirable minimum electron emission energy level. In addition, the cesium halide material can also contain other materials, beside cesium and halogen.

The alkali halide has to be activated before it can emit electrons at the desired efficiency and yield levels, and to have a lower minimum electron emission energy level than the theoretical minimum electron emission energy of the same but untreated alkali halide material. The activation treatment reduces the minimum electron emission energy level of the alkali halide by at least 75%, and can even lower the energy level by at least 50%. For example, without activation, the theoretically determined energy gap of an exemplary alkali halide such as CsBr is 7.8 eV, however, after activation the minimum emission energy of the same CsBr material can be reduced to less than about 5 eV, for example, about 4.8 eV, and can even be about 3 eV. The significantly lower minimum electron emission energy level makes it practicable to use the electron-emitting material in conventional applications.

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In one version of the activation method, the electron-emitting material 24 is activated by irradiating the alkali halide material with a radiation having a sufficiently high energy level and for a sufficiently long time period to create an activated material having a lower minimum electron emission energy level. The radiation may be, for example, UV, X-ray, visible light, or electron beams. During irradiation, it is believed that the reduced minimum electron emission energy level is achieved by the migration of alkali metal atoms to form color centers in the bulk of the alkali halide material and a capping layer on its surface. A color center (or F-center) is a lattice defect in a crystalline solid comprising a vacant negative ion site and an electron bound to the site. Such defects absorb radiation having a wavelength that corresponds to the band

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gap energy level created by the defect, and can make certain normally transparent crystals appear colored, or can make colored crystals change color. The color centers and their corresponding radiation absorption bands may be caused by one or more of hole center, electron centers, di-vacancy and di-hole centers, and even Frenkel defects. The presence of the color centers can be detected by observing a change in a color of the material, if such a color change is in the observable visible spectrum. Scanning a series of sequentially incremented wavelengths across a specimen of the activated material and detecting the resultant absorption spectrum can be used to detect the color centers. The detected absorption spectrum has absorption peaks corresponding to the wavelengths of the incident radiation that is absorbed by the color centers. Thus, the un-activated alkali halide absorbs a first level of a radiation having a wavelength that falls in the absorption band of color centers to form the activated alkali halide, which then absorbs a second level of the same radiation to emit electrons. Photoelectron spectroscopy can also be used to probe the electronically excited states of alkali-halide material with excess electrons, in which the excess electrons are pumped up to their excited states by one laser pulse before being driven into the continuum by a second laser pulse.

Activation of the alkali halide material is affected during irradiation when the alkali halide material is heated to a temperature of from about 60 to about 300°C. At relatively low temperatures of less than about 100°C, the heat increases the diffusion of alkali metal atoms, such as the cesium, to the surface of the alkali halide film to form a capping surface layer having a higher concentration of alkali atoms than that present in the bulk of the interior region of the activated material. However, the material can be deactivated when it is heated to a sufficiently high temperature. The higher surface concentration of alkali metal atoms in the surface reduces the effective work function of the alkali halide material by lowering the energy required to excite electrons out of the surface. Typically, directing a laser beam having an output of a few mWatts for a time period of a few hours, such as about 180 minutes (3 hours), on the electron-emitting material is sufficient to generate the surface activated layer.

In the activation process, the incident radiation causes the alkali metal atoms, such as the cesium atoms, to migrate to the surface of the electron-emitting material **24** to form a thin capping layer having a higher concentration of alkali metal than the surrounding bulk material. The capping layer can have a thickness from at

least a fraction of a monolayer to several monolayers of atoms. It is believed that the capping surface layer of alkali metal cooperates with the underlying bulk of the alkali halide material to form a dipole that reduces the electron emission energy at the surface of the resultant electron-emitting material **24**.

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For example, in an electron-emitting material **24** comprising cesium halide, the cesium halide material is deposited as a layer on a substratum and then activated to have a capping layer of cesium atoms **28** on its surface. When photons irradiate the electron-emitting material **24**, the emission surface **30** with the higher cesium concentration of the capping layer provides an effectively lowered minimum electron emission energy level at the surface of the material **24** that allows longer-wavelength (lower energy) photons to generate electron emission from the activated material. For example, by deep-UV light activation, the minimum electron emission energy level at the emission surface **30** of a cesium bromide or cesium iodide layer can be reduced to less than 5 eV, such as about 4.8 eV or 3.6 eV or even about 2.1 eV. Then, a photon source such as an argon-ion laser beam **32** with a wavelength of at least about 257 nm, for example, the laser beam **32** can have a wavelength of about 364 or 532 nm can be used to irradiate and cause electron emissions from such an electron-emitting material **24**. The photoyield of the 532 nm laser beam is significantly lower than the corresponding one for the smaller-wavelength laser beam, such as the 257 nm laser beam.

In one version, the electron-emitting material **24** comprises activated cesium bromide material. This activated cesium bromide material can yield a quantum efficiency of at least about 0.1% when irradiated with approximately 4.8 eV photons (257 nm), and an energy spread of about 1 eV. This version is advantageous because conventional photoemitters like Au have a much lower efficiency and are susceptible to surfacecontamination.

In another version, the electron-emitting material **24** comprises cesium iodide material. The cesium iodide material is advantageous because it may be more stable in terms of temperature resistance or corrosion resistance.

The activated alkali halide electron-emitting material also provides good photoyields that exhibit low degradation over time in a vacuum environment. The

photoyield is a measure of the electron emitting efficiency of the electron emitter layer.

An activated alkali halide, for example, activated CsBr, provides a photoemission electron yield at least about 20 nA/mW, and more typically, even about 200 nA/mW.

In contrast, the same un-activated CsBr photocathode generally provides no yields or  
5 yields of less than about 2 nA/mW. This demonstrates an improvement in yield of a factor of 10 to about 100 times. Furthermore, unlike conventional photocathode materials, the electron yield reduces only marginally after operation for extended periods in vacuum environments. For example, a photocathode having an activated CsBr electron-emitting material with an argon ion laser can provide a photoyield of  
10 greater than 200 nA/mW that remains stable at these levels in a vacuum environment for an extended time period, as shown in Figure 8. The output was found to remain stable for more than 150 hours without appreciable degradation.

The lower minimum electron emission energy level of the activated  
15 material also allows use of activated beam sources that are well characterized and commonly used systems, such as an argon ion laser. An argon ion laser has a fundamental wavelength of at least about 514 nm, which can be frequency multiplied by the BBO crystal to have a divided wavelength of at least about 257 nm. The divided wavelength is equivalent to an energy level of about 4.8 eV, which is higher than the  
20 minimum electron emission energy level of activated CsBr of about 2 eV. The same argon ion laser cannot be used to generate electrons using un-activated CsBr, which in its untreated form has an energy gap of 7.8 eV that would require a laser source having a wavelength smaller than 158 nm, which is smaller than that being produced by the argon ion laser. For these reasons, activated electron-emitting material **24**  
25 comprising CsBr, emits electrons more reliably and with better yields than the un-activated material.

The electron emitter layer of the photocathode **20** can be manufactured in a photocathode deposition system **50**, an embodiment of which is illustrated in  
30 Figure 2. The photocathode deposition system **50** comprises a sublimator chamber **51** to deposit both a conductor film **26** and an electron-emitting material **24** on a substratum **20**. A transfer or analysis chamber (not shown) can also be used for post-deposition analysis of the photocathode **20**. The substratum **22** is placed in the sublimator chamber **51**, and effusion cells **52** are used to sublime alkali halide  
35 material for deposition on the substratum **22**. Channels **53** are provided between the

chambers to allow transfer of the substratum **22** between the chambers without exposure to the external atmosphere.

The sublimator chamber **51** has stainless steel walls **54** and an ultra-high vacuum pump **55**, such as an ion pump, to maintain an ultrahigh vacuum of from about  $10^{-8}$  to about  $10^{-11}$  Torr. Liquid nitrogen shrouding is used to provide cold surfaces within the sublimator chamber **51** to reduce unwanted contaminants. The substratum **22** is mounted on a holder **58**, which is maintained at a selected temperature for film growth by a power supply **56**. A temperature instrument (not shown) may also be provided. An optical pyrometer or thermocouple can be used to measure the temperature of the substratum **22**.

An electron beam evaporator **57** is provided in the sublimator chamber **51** to evaporate material onto the substratum **22** to form the conductor film **26**. The conductor film that transmits the photon beams **32** with sufficiently low attenuation to allow the beams to pass through and still irradiate the electron-emitting material with sufficient energy. The conductor film can be a molybdenum film having a thickness of less than about 10 nm to provide an attenuation of less than about 20% at 257 nm. The evaporator **57** operates by directing a beam of electrons onto a metal wire. The conductor film can also be made of other metals, such as Mo, Cr, Ta, that have low ultraviolet attenuation, good wetting, and strong adhesion.

The effusion cell **52** also has a crucible **59** for sublimating alkali halide material **60** placed therein. The crucible **59** is made of a high temperature material, such as ceramic, graphite, tantalum, molybdenum, or pyrolytic boron nitride. The crucible **59** is secured to a frame **63** connected to a flange **64** for attachment of the effusion cell **52** to the sublimator chamber **51**. The sublimator chamber **51** is evacuated to form an ultra-high vacuum oxygen-free environment in which the effusion cell **52** can operate. A heating assembly **62** surrounding the crucible **59** heats the material **60** in the crucible **59** to control the sublimation of the source material **60** from solid to vapor form. For example, in one embodiment, the source material **60** is heated to a temperature of from about 60 to about 300 °C. The evaporated molecules **61** generated by evaporation of the alkali halide material **60** in the crucible **59** deposits on the conductor film **26** to form an epitaxial film of alkali halide material.

After deposition of the halide material **60** on the substratum **22**, the deposited material is activated to form an electron-emitting material **24** having a reduced minimum electron emission energy level at its surface. In one activation method, the deposited alkali halide material is irradiated with a radiation such as ultra-violet radiation having a wavelength  $<300\text{nm}$ , such as deep-ultraviolet radiation having a wavelength in the range of from about 190 to about 532 nm. A suitable radiation source for an electron emitter layer comprising CsBr is, for example, an argon-ion laser. The activation is performed by directing the argon-ion laser beam onto the deposited electron-emitting material, in vacuum, for a time period of from 120 to about 240 minutes. An example of the progress of the activation process is illustrated in Figure 1. The activation can be performed insitu in an electron generating apparatus or the photocathode may be activated in a separate vacuum chamber and transferred to the operating chamber under vacuum. In the irradiation step, a lower minimum electron emission energy level is achieved by the migration of alkali metal atoms to form residual color centers and a surface-capping layer having a higher alkali metal atom concentration.

An embodiment of an electron beam apparatus **100** having a photocathode with an activated electron-emitting material is illustrated in Figure 3. The apparatus generates multiple electron beams **34** that are scanned across a workpiece **105**. The workpiece **105** can be a blank mask; a silicon wafer; a compound semiconductor wafer; a printed circuit board (PCB); or a multichip module (MCM). In one embodiment, the electron beam pattern is imprinted in a mask comprising an electron-sensitive resist coating **115** on a workpiece **105** comprising glass or quartz, which is used in the fabrication of integrated circuits (IC). After exposing the workpiece mask to electron beams **34**, the exposed resist layer **115** is developed to form a resist pattern on the mask. The embodiments of the apparatus **100** and workpiece **105** illustrated herein are examples, and should not be used to limit the scope of the invention, and the invention encompasses equivalent or alternative versions, as would be apparent to one of ordinary skill in the art.

The electron beam apparatus **100** includes a photon source section **120** coupled to an electron beam section **125**. The photon source section **120** may include a beam source **130**, a beam modulator **135**, optical system **140**, and beam splitter **150**, as illustrated in Figure 4. In one version, the beam source **130** comprises a laser **131**,

such as an argon ion laser. The beam source **130** may also comprise a frequency multiplier **132** to increase the frequency of the laser beam **32** emitted by the laser **131**.

For example, the frequency multiplier **132** may comprise a beta barium borate (BBO) crystal that approximately doubles the frequency of the laser beam **32**. For an argon-ion produced laser beam having a fundamental wavelength of about 514 nm, a BBO crystal can receive the laser beam and double its frequency; in other words, halve its wavelength to about 257 nm. Alternatively, the beam source **130** may also comprise a frequency doubled diode-pumped laser source. In one example, the diode-pumped laser source operates at a fundamental wavelength of about 532 nm. A laser having a wavelength of 364 nm can also be used.

In operation, a laser beam **32** is generated by the laser **131** is split by a beam splitter **150** into an array of spaced apart individual laser beams. The laser beam array is then directed to a beam modulator **135** that modulates the intensities of each of the laser beams **32**. For example, the beam modulator **135** may comprise an array of acousto-optic modulators (AOM), which switch the laser beams **32** on or off by acoustically diffracting the laser beams in response to an RF signal, or set the transmitted photon flux of each individual beam to a predetermined intermediate value.

In one embodiment, the laser beam **32** is split by a beam splitter **150** into an array comprising 32 individual beams, and a beam modulator **135** comprising a matching number of 32 AOM beam modulator elements is used to modulate the split beams. In an AOM array, the modulation of the photon intensity is achieved by applying RF power to the individual AOM channels. Applying different levels of RF power can be used for fine modulation of the light intensity. In another embodiment, the beam modulator **135** comprises a spatial light modulator (SLM) such as a micromechanical diffracting device. SLMs can be advantageous because they can modulate a larger number of laser beams, such as at least about 100 laser beams. A multiple gray level, multiple pass writing strategy may also be used, in beam modulation. Furthermore, another beam modulator (not shown) may be inserted in the optical system upstream of the beam splitter **150** to act as a fast auxiliary blanker. This additional beam modulator may be used during scan retrace when additional modulation is needed. In one illustrative embodiment, a 300 MHz carrier frequency is used to diffract the laser beams with an approximately 10 nsec pixel time.



The beam splitter **150** may include optical light lenses focused on a desired plane of the electron beam section **125**. The laser beam **32** from the laser beam source **130** may also be actively controlled by automatic beam centering mirrors **160** so that alignment to the optical train, both in position and angle, is maintained. An attenuator **165**, which may comprise a combination polarization-rotating element and polarizing beam splitter, adjusts the laser power to a range suitable for operation of the system while allowing the beam source **130** to operate in a power range optimized for reliability and stability. A spatial filter **170** can remove undesirable sections of the laser beams intensity profile. An anamorphic relay **172** can be provided to create a round beam exiting this aperture and relay it to the diffractive optical element (DOE) **175** inside a brush module **180**. The DOE **175** is a grating that produces a plurality of laser beams **32**. The laser beams **32** are focused by lenses of the brush module **180** to a region typically underneath the additional beam modulator. A mechanical shutter **185** before the brush module **180** is used to block radiation from reaching the electron beam section **125** when the electron beam apparatus **100** is not exposing the workpiece **105**.

The individual modulated laser beams **32** are demagnified by the optical system **140**. A K-mirror **190** allows for rotational adjustment of the linear array of laser beams **32** exiting the additional beam modulator. A wave plate **195** aligns the polarization of the beams for optimal focusing through birefringent substratums such as sapphire. A lens element **200** after the wave plate **195** focuses the laser beam array onto a focal spot on a steering mirror **205**. Before reaching the steering mirror **205**, the zero-order (undiffracted) light from the beam modulator **135** is blocked by a zero-order beam stop **210**. The steering mirror **205** allows for small positional adjustment of the spot array at the final image plane of an objective lens **215**. The zoom optics and stigmator **220** relay the focal spot into the pupil of the objective lens **215**. Tilted plates inside the zoom optics and stigmator **220** provide adjustment capability to ensure that the focus of the spots onto the electron beam section **125** occurs in the same plane whether measured along the direction of the array of spots or perpendicular to it. Movable lenses within the zoom optics and stigmator **220** allow for slight magnification adjustment of the array of laser beams **32**.

Referring to Figures 3 and 5, below the photon source section **120**, the electron beam section **125** converts the photon beam image generated by the photon

source section **120** into a corresponding electron beam image. The electron beam section **125** may comprise a vacuum column **225** containing a vacuum environment in which electron beams **34** can be generated to expose the workpiece **105** to an electron beam image. The vacuum column **225** comprises walls **230** that are substantially vacuum-tight and are typically made of a material such as aluminum. One or more vacuum pumps (not shown) are provided to evacuate the vacuum column **225** to create and maintain the vacuum environment. In one embodiment, the vacuum pumps provide a first vacuum environment at the top portion of the vacuum column **225**, and a second vacuum environment, which may have a different vacuum pressure at the bottom portion of the vacuum column **225**. For example, the first vacuum environment may be at a gas pressure of about  $10^{-9}$  Torr and the second vacuum environment may be at a gas pressure of about  $10^{-6}$  Torr. A pressure barrier may also be provided between the vacuum environments to maintain the pressure difference.

The electron beam section **125** includes a photocathode **20** according to the present invention, and electron beam elements such as an anode **240** and electron optics **245**. During installation of the photocathode **20** in the electron beam apparatus **100**, the photocathode **20** may be transferred within a continuous vacuum environment into the electron beam section **125**. In operation, the optical system **140** focuses the array of laser beams **32** exiting the beam modulator **135** onto a photocathode **20**. The photocathode **20** receives the laser beam image and generates corresponding multiple electron beams **34** that form an electron beam image.

The photocathode **20** forms an extraction field between itself and the anode **240** to draw the electron beams **34** from the photocathode **20** and accelerate the electron beams **34** toward the workpiece **105**. For example, the extraction field may have a strength of from about 5 to about 10 kV/mm. The electrons are accelerated to an initial energy level to form defined electron beams **34**. The energy level is selected to be sufficiently high to substantially prevent interactions between the electron beams **34**. When the electron beams **34** are moving vertically at a higher velocity, lateral interactions between the electron beams **34** are typically less significant than when the electron beams **34** are moving at lower velocities. In one embodiment, the electron beams **34** are accelerated to energies of from 1 keV to about 60 keV, such as about 50 keV. The electron beams **34** may have a brush width of from about 40 to about 90 microns, such as about 65 microns. Each electron beam

**34** has a width of from about 270 to about 330 nm. When a voltage is applied to the anode **240**, the electrons are accelerated and focused to form a multibeam virtual electron image of the photocathode emission surface corresponding to the laser beam image generated by the laser beam source **131**. In one embodiment, the  
5 photocathode **20** is biased at about -50 kV, and is separated from a grounded anode **240** by an accelerating gap. The anode **240** is typically a planar electrode with an aperture in the center.

The electron optics **245** shape the electron beams **34** to focus,  
10 demagnify, stigmatize, or align the electrons. Optionally, an electron field lens **260** near the photocathode **20** is used to reduce off-axis aberrations in demagnification lenses **265** that follow. A version of exemplary electron optics is described in commonly-assigned U.S. Patent No. 6,215,128 by Mankos et al., entitled "Compact  
15 Photoemission Source, Field and Objective Lens Arrangement for High Throughput Electron Beam Lithography", filed on March 18, 1999, which is hereby incorporated by reference in its entirety. The field lens **260** collimates the electrons exiting the accelerating region above the anode **240** and forms a crossover in the plane of a beam-limiting aperture **270**. The virtual image created by the field lens **260** is then  
20 subsequently demagnified by the demagnification and objective magnetic lenses **265**, **280** to form an array **285** of focused electron beams **34**. Sets of alignment coils **290** are used to center and stigmatize the electron beam array **285** in the beam-limiting aperture **270** and in the objective lens **280**.

In one embodiment, a beam scanner **295** comprising a set of magnetic  
25 beam deflection coils is used to scan the array **285** of individually modulated electron beams **34** across the workpiece **105**. Another set of magnetic deflection coils **300** performs dynamic stigmatization and focus as the electron beam array **285** is scanned across a field of the workpiece **105**. This allows dynamic stigmatization, focus, or x/y deflection corrections to be applied to different parts of the scan field.

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The electron beam pathway traversed by the electron beams **34** can be along a straight pathway, a curved pathway, or a series of redirected pathways. Thus, the apparatus components may be vertically oriented in a column above the workpiece **105**, or oriented in an angled configuration (not shown), such as a right-angled  
35 configuration, or may be oriented in a curved configuration (also not shown).

The electron beam apparatus **100** further comprises a workpiece support **305** capable of supporting the workpiece **105**. The support **305** may comprise an electrostatic chuck (not shown) capable of holding the workpiece **105** against the support **305**. The electron beam generator **100** may also comprise support motors capable of moving the support **305** to precisely position the workpiece **105** in relation to the electron optics **245** or to move the workpiece **105** to scan the electron beams **34** across the workpiece **105**. For example, the support motors may comprise electric motors that translate the support **305** in the  $x$  and  $y$  directions along an  $x$ - $y$  plane parallel to the workpiece surface, rotate the support **305**, elevate or lower the support **305**, or tilt the support **305**. The electron beam apparatus **100** may further comprise support position sensors capable of precisely determining the position of the support **305**. For example, the support position sensors may reflect a light beam (not shown) from the support **305** and detect the intensity of the reflected beam, where interferometric analysis indicates the distance between the workpiece support **305** and the support position sensors.

When generating a pattern in an electron-sensitive resist **115** of a workpiece **105**, exposure throughput refers to the area of the pattern exposed on the workpiece **105** per unit time, and determines the speed of pattern generation. A first factor affecting throughput is the total current needed to generate the pattern. A certain fraction of the electron-sensitive resist **115** is to be exposed. To a first approximation, this exposure occurs after a particular electron dose, which can be calculated for a resist **115** of given sensitivity. The throughput is determined by the time required to deliver this dose, which is proportional to the maximum total electron current. This total current is proportional to the number of electron beams  $N_b$  and the current  $I_b$  delivered by each electron beam **34** of the array **285**. Thus the time  $\delta$  to expose a given area is  $\delta = AS/N_b I_b$ , where  $A$  is the area to be patterned and  $S$  is the resist sensitivity (charge density required to expose the resist). High throughput can be achieved by using a sufficiently large number of electron beams **34** and a sufficiently large current in each electron beam **34**.

The electron beam apparatus **100** further comprises a controller **400** comprising a suitable configuration of hardware and software to operate the components of the electron beam apparatus **100** to generate an electron beam pattern

on the workpiece **105**. An exemplary controller **400** is illustrated in Figure 3. For example, the controller **400** may comprise a central processing unit (CPU) **405** that is connected to a memory **410** and other components. The CPU **405** comprises a microprocessor, such as a complex instruction set computer (CISC) microprocessor, for example a Pentium (TM) microprocessor commercially available from Intel Corporation, Santa Clara, California, or a reduced instruction set computer (RISC) microprocessor, capable of executing a computer-readable program **415**. The memory **410** may comprise a computer-readable medium such as hard disks **420** in a redundant array of independent disks (RAID) configuration, removable storage **425** such as an optical compact disc (CD) or floppy disk, random access memory (RAM) **430**, and/or other types of volatile or non-volatile memory. The interface between a human operator and the controller **400** can be, for example, via a display **435**, such as a cathode ray tube (CRT) monitor, and an input device, such as a keyboard **440**. The controller **400** may also include drive electronics **445** such as analog and digital input/output boards, linear motor driver boards, or stepper motor controller boards.

The computer-readable program **415** generally comprises software comprising sets of instructions to operate the apparatus components, and an apparatus manager **450** to manage the instruction sets, as illustrated in the exemplary version of Figure 6. The computer-readable program **415** can be written in any conventional programming language, such as for example, assembly language, C, C++ or Pascal. Suitable program code is entered into a single file, or multiple files, using a conventional text editor and stored or embodied in the memory **410** of the controller **400**. If the entered code text is in a high level language, the code is compiled, and the resultant compiler code is then linked with an object code of pre-compiled library routines. To execute the linked, compiled object code, the user invokes the feature code, causing the CPU **405** to read and execute the code to perform the tasks identified in the computer-readable program **415**. Using a keyboard interface, a human user enters commands or registration parameters into the computer-readable program **415** in response to menus or screens displayed on the display **435**. The computer-readable program **415** may include instruction sets to, for example, control the positioning of the workpiece support **305** (instruction set **455**), locate fiducial marks on the workpiece **105** (instruction set **460**), control beam modulation (instruction set **465**), control data compression (instruction set **470**), and control the retarding of the electron beams **34** (instruction set **473**). If the electron

beam apparatus **100** is used to inspect the workpiece **105**, the computer-readable program **415** may further comprise an instruction set to evaluate a signal from the detectors **342** to generate a pattern representative of the structure of the workpiece **105** (instruction set **477**). This workpiece inspection instruction set **477** may also  
5 comprise program code to determine a property of the workpiece **105**, such as a defect or critical dimension, from the evaluated signals. The instruction sets may receive parameters, such as a data file corresponding to the support position, the fiducial mark locations, the electron beam pattern, properties of the workpiece **105**, or instructions entered by the human operator.

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The controller **400** is adapted to generate, send, and receive signals to operate the apparatus components to generate a pattern by directing electron beams **34** onto the workpiece **105**. For example, the controller **400** may send signals to the beam modulator **135** to control modulation of the electron beams **34** to the desired  
15 intensity levels, such as in correspondence to electron beam pattern data to write a corresponding pattern on the workpiece **105**. The beam modulator **135** may also be controlled to scale the electron beam pattern in the scanning direction by timing the beam pulses, and the support motors may also receive real-time instructions from the controller **400** to control the position of the workpiece **105** to scale, rotate, or offset the  
20 pattern generated by the electron beams **34**. As another example, the controller **400** may also operate a fiducial mark locator **340** by receiving measured locations of fiducial marks on the workpiece **105** and comparing them to intended locations to determine the deviation of each fiducial mark, thereby calculating the position of the workpiece **105**.

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The controller **400** may control the beam modulator **135** and beam scanner **295** of the electron beam apparatus **100** to scan the electron beams **34** across the workpiece **105** according to a raster method, or alternatively according to a vector method. Depending on the scanning method used in generating a pattern on  
30 the workpiece **105**, pattern data that are stored in the memory **410** and communicated to the beam modulator **135** are also different. Figure 7 is a block diagram showing a data processing path for a raster scanned electron pattern. In a raster method, the pattern data **475** are processed into a bitmap **480** by a rasterizer **485** and the bitmap **480** is stored in the memory **410**. An exemplary rasterizer **485** is described in  
35 commonly-assigned U.S. Patent No. 5,533,170 by Teitzel et al., entitled "Rasterizer for

a Pattern Generation Apparatus", filed on November 22, 1994, which is hereby incorporated by reference in its entirety. Thereafter, a corrector **490** corrects the bitmap to compensate for proximity effects, heating effects, or other undesirable effects. A sequencer **495** then sequences the corrections to apply to the sequenced  
5 bitmap to modulate the electron beams **34**. Control of pixel dosage is determined by the modulation of the electron beams **34** as a function of time. The electron beams **34** are scanned across the workpiece **105** in a substantially predetermined sequence of parallel scan lines to generate the pattern on the workpiece **105**.

10 In a vector scanning method, in contrast, the pattern data are stored as vectors. For example, data corresponding to a line can be stored as a vector comprising a starting position, a length, and a direction. Additionally, certain other shapes may be stored in a way that refers to the characteristic dimensions of the shapes. The electron beams **34** are scanned across the workpiece **105** along paths  
15 that correspond to the pattern vectors. For example, to draw a line, the beam scanner **295** could deflect an electron beam **34** to the starting position in a first step, the beam modulator **135** turns on the electron beam **34** in a second step, the beam scanner **295** deflects the turned-on electron beam **34** through the length of the line in a third step, and the beam modulator **135** turns off the electron beam **34** in a fourth step.

20 Typically, the electron beams **34** are spatially distributed such that optical interference and other crosstalk between them are reduced or eliminated. However, typically a final exposed pattern in the resist layer **115** produced by raster scanning is composed of overlapping spots, which can be accomplished by employing an  
25 interlaced scan print strategy and writing with multiple passes. The controller **400** may contain pattern data in the memory **410** in either flat or hierarchical formats. The flat formats contain the pattern information in a raw form that is not organized by hierarchy or otherwise compressed. In contrast, the hierarchical formats contain the pattern information in a compressed hierarchical organization that expedites transmission from  
30 the memory **410** to the beam modulator **135**.

An exemplary embodiment of an electron beam inspection apparatus **500** is schematically illustrated in Figure 9. The illustration is provided as an exemplary embodiment and should not be used to limit scope of the invention or this embodiment.  
35 Generally, the apparatus **500** directs electron beam **34** toward a substrate **105** and

subsequently detects back-scattered electrons **537**, secondary electrons **539**, and transmitted electrons **541**. The detected electrons can be used to generate an image representative of the substrate **105**. For example, electron beams reflected from the substrate **105** can be used to determine a surface topography of the substrate **105**, or  
5 electrons can be transmitted through the substrate **105** to determine an internal composition of the substrate **105** or to irradiate the substrate **105**. Any electron generated image can be used to determine properties of the substrate **105**, such as to accurately locate defects, measure dimensions of features of the substrate **105**, or measure distances between two or more points on the substrate **105**. For example,  
10 after manufacturing, a substrate **105** can be inspected to determine whether critical dimensions of features formed on the substrate are within a preselected tolerance range or are properly shaped. The electron beam inspection apparatus **500** is capable of inspecting semiconductor substrates, X-ray masks and other conductive substrates. The apparatus **500** can also be used in various modes of operation, for example,  
15 images from two sections of the same substrate **105** can be compared with each other, or the image from the substrate **105** can be compared with an image from a database that represents the design goal.

The electron beam inspection apparatus **500** comprises enclosing walls  
20 **501** to contain a vacuum environment generated by vacuum pumps (not shown). The apparatus **500** comprises a photon source section **503** and an electron beam inspection section **505**. The photon source section **503** produces and delivers a single beam or multiple, independently-controllable radiation beams **502** to the electron beam inspection section **505**. The section **503** may comprise the photon source section **120**  
25 from the apparatus **100** as previously discussed, or other photon sources, such as a lamp that produces photons with energies above at least about 3 eV.

Disposed below the photon source section **503** is the electron beam inspection section **505**, comprising a photocathode **20** to receive the radiation beam  
30 **502** and generate an electron beam **34**. The photocathode **20** comprises an activated alkali halide material that emits electrons when excited with radiation as described. Power supplies **507**, **509** deliver bias conditions to the photocathode **20** and the anode **240** to form an extraction field between the photocathode **20** and the anode **240**. For example, the extraction field may have a strength of from about 0.1 to 5 kV/mm. In



one embodiment, the photocathode **20** is biased at about 1kV. The anode **240** is typically a planar electrode with an aperture in the center.

The electron beam inspection section **505** also comprises electron optics to focus, control, deflect, and otherwise shape the electron beam **34** emitted by the photocathode **20**, which is also referred to as the primary beam **34**. An upper lens **513** may be disposed below the photocathode **20** and anode **240** to collimate the electron beam **34**. An upper deflector **515** may also be optionally disposed near the upper lens **513** for alignment, stigmatism, and blanking of the electron beam **34**. The upper deflector **515** may be, for example, an electrostatic deflector. A beam limiting aperture **517** is disposed below the upper lens **513** and upper deflectors **515** to provide further beam shaping and comprises several holes. A pair of electrostatic beam deflectors **519** are disposed below the beam limiting aperture **517** to control the deflection of the beam **34** as it scans the substrate **105**. The beam deflectors **519** may also be used to control the incident primary beam **34** such that interference with other electrons generated by the incidence of the primary beam **34** on the substrate **105** are minimized. A lens **521** is disposed below the beam deflectors **519** to refocus the electron beam **34**.

The substrate **105** to be inspected is held and positioned by an x-y stage **523** disposed below the lens **521**. The stage **523** is controlled by a stage servo **525**. Interferometers **527** disposed about the stage **523** and substrate **105** are used for positioning and alignment of the substrate **105**. Communication between the stage **523**, stage servo **525**, and the interferometers **527** is performed by a system controller **529**.

The electron beam inspection apparatus **500** can detect one or more of secondary **539**, back-scattered **537**, and transmission electrons **541**. To detect secondary electrons **539**, the apparatus **500** comprises secondary electron deflectors **531** and a secondary electron detector **533**. The secondary electron deflector **531** is disposed near the lens **521** and is capable of deflecting secondary electrons **539** to the secondary electron detector **533** based on their energy levels. In one version, the secondary electron deflector **531** comprises a Wien filter that only allows charged particles having a threshold energy to pass uninhibited and deflects the path of

particles at other energies. The Wien filter is tuned to the incident primary electron beam energy to deflect the lower energy secondary electrons **539**. The secondary electron detector **533** receives deflected secondary electrons **539**, and may be a reverse biased high frequency Schottky barrier detector. Other types of semiconductor detectors may also be used. The stage **523**, substrate **105**, and portions of the lens **521** may be biased in such a way as to increase the energy levels of secondary electrons **539** to allow their efficient collection, and bias conditions are coordinated with the tuning of the Wien filter.

The back-scattered electron detector **535** is disposed annularly about, and above the lens **521**, and comprises a hole in the center to allow passage of the primary electron beam **34**. Back-scattered electrons **537** typically have a higher energy than secondary electrons **539**, and may be further accelerated by bias conditions on the stage **523**, substrate **105**, and lens **521**, to allow them to pass relatively uninhibited by the secondary electron deflector **531**. The apparatus **500** may also be operated such that the secondary electron deflector **531** is turned off and thus only back-scattered electrons **537** will be detected. The back-scattered electron detector **535** may be a Schottky barrier detector similar to other detectors, but with the above mentioned hole in the center.

To allow inspection of partially transparent substrates, a transmission electron detector **543** is located below the stage **523**. A transmission lens **545** is disposed below the stage **523** and above the transmission electron detector **543**. The transmission electrostatic lens **545** is used to spread the transmitted electron beam **541** to a diameter suitable for detection by the transmitted electron detector **543**, which may also be a Schottky barrier detector.

The system controller **529** coordinates the operation of the apparatus **500** and its subsystems, which include deflection controllers **547**, the stage servo **525**, lens controllers **549**, an inspection apparatus computer readable program **555**, and an operator interface **551**. The system controller **529**, as illustrated in Figure 10, comprises memory **410**, CPU **405**, drive electronics **445**, and hardware modules **553**. The memory **410** may further comprise hard disks, RAM, and removable storage (all of which are not shown). The drive electronics **445** function as the interface between the

system controller **529** and the various other subsystems of the apparatus **500**. The hardware modules **553** may comprise specialized hardware to facilitate the function of the system controller **529**. The hardware modules **553** are removable and may be periodically exchanged for updated modules. The deflection controllers **547** control the operation of the various beam deflectors. The inspection apparatus computer readable program **555** includes instruction sets that the system controller **529** may use to operate the apparatus **500**. The instruction sets comprise image analysis instructions **557**, deflection controller instructions **559**, stage servo instructions **561**, and lens controller instructions **563**. The image analysis instructions **557** comprise image database instructions **565**, image comparison instructions **567**, image processing instructions **569**. The image analysis instruction sets **557** include instructions for such purposes as storing image scan data, reading and retrieving image data from a database, comparing scanned image data with images from the image database or other scanned data, and high level image processing algorithms. The operator interface **551** comprises at least a keyboard **440** and a display **435** and relays information to a human operator and accepts commands. The interface **551** may also comprise other input and output devices such as a mouse, floppy disk drive, compact disc drive, and a printer (all not shown).

During operation of the apparatus, the substrate **105** to be inspected is placed beneath the electron beam **34** on the x-y stage **523**. Alignment of the substrate **105** is achieved by scanning the substrate **105** with the electron beam **34** and observing the image on the display **435**. The apparatus **500** then directs an electron beam **34** at the substrate **105** and detects secondary electrons **539** generated by the beam **34**, the back-scattered electrons **537** from the beam **34** and transmitted electrons **541** which pass through the substrate **105**. Data collection and analysis of the scan is performed by the system controller **529** and the inspection apparatus computer readable program **555**. The position and movement of the stage **523** during the inspection of the substrate **105** is controlled by the stage servo **525**, interferometers **527**, and the system controller **529**.

When comparing the substrate **105** to a database image, data from the scan is stored in the memory **410**, and a comparison to the database image is performed by the system controller **529** using the image analysis instructions **557**.

Likewise, when comparing two sections of the same substrate **105**, the stage servo **525** moves the stage **523** so that the electron beam **34** alternately scans each section or subsections. The scan data of the first section or subsection is stored in the memory **410**, and then this data, along with the scan data of the second section or subsection is processed by the system controller **529** and the image analysis instructions **557**. Various defect detection algorithms may be implemented via the image analysis instructions **557**, which may interpret the comparison of the image data according to algorithms. After the substrate **105** has been inspected, a list of defects, together with their locations, is displayed on the display **435** and the operator can then initiate a defect review via the keyboard **440**. In response to operator commands, the apparatus **500** may locate and provide scans of the neighborhood of each defect and displays the image to the operator on the display **435**.

Two important applications of the electron beam inspection apparatus **500** are the detection of small physical defects and the detection of defects buried well beneath the surface of the substrate **105**. Detection of small physical defects is becoming increasingly difficult. Shrinking feature sizes and increasing aspect ratios are pushing inspection of substrates beyond the inherent limits of optical inspection. The electron beam inspection device **500** can typically achieve higher resolution and higher depth of field than optical inspection devices, making electron beam inspection an increasingly important tool for the processing of substrates.

Defects buried well beneath the surface of the substrate **105** are also an important application and are essentially invisible to optical devices. Voids in contact and via plugs can often be hidden beneath several layers of subsequently deposited material. Incomplete etch or excess polymer buildup during the formation of holes for contacts and vias are also a concern. Buried defects can be discovered by electron beam inspection even if the electron beam inspection apparatus **500** can not form a direct image of the area of concern. Buried defects can be identified using a technique known as voltage contrast. Upon illumination by an electron beam **34**, a defective hole charges up differently than a non-defective hole. The bad hole either glows more or less, depending on image conditions, than the good ones do in the electron beam image. A defective plug can also be found this way. Upon illumination by the electron beam **34**, the higher resistance of the defective plug causes it to glow either more or less brightly in the image, thus identifying itself.

Although the present invention has been described in considerable detail with regard to certain preferred versions thereof, other versions are possible. The present invention could be used with other electron beam apparatuses **100** or other equivalent configurations as would be apparent to one of ordinary skill in the art. For example, the electron beam apparatus **100** may generate a pattern by generating and modulating the electron beams **34** directly rather than in the photon source section **120**. Also, the electron beam apparatus **100** may generate the electron beams **34** by illuminating the photocathode **20** with other electron beams from an electron beam source rather than with the laser beams **32** from the photon source section **120**. Thus, the appended claims should not be limited to the description of the preferred versions contained herein.